A Near-Term Propulsion System for Human/Robotic Exploration of the Solar System

Terry Kammash
University of Michigan
Ann Arbor, MI 48109

- Name of Propulsion Concept: LAPPS "Laser Accelerated Plasma Propulsion System"
- This system is expected to evolve out of current research on the use of "ultrafast" lasers in accelerating charged particles to relativistic energies.
- Current research at the University of Michigan and elsewhere in the world has shown that lasers with 10's – 100's of joules of energy and several hundred femtoseconds (1 fs = 10^{-15} sec) pulse length can produce proton beams containing more than 10^{10} – 10^{14} particles at mean directed energies of 10 – 70 MeV.
- Research has shown that rep rates of 10 – 1000 Hz are also feasible and that means LAPPS is capable of producing sizable thrusts.
- Based on some present-day experimental data, a LAPPS propulsion system can produce several million seconds of specific impulse at tens of millinewtons of thrust. It will require, however, a nuclear reactor system producing about a MWe to drive it.
- Such a system is almost achievable with present-day technology. It can make a robotic fly-by mission, for example, to Pluto in 67 years, to Jupiter in 22 years, and a similar one to Mars in about 8 years.
- Advancements in ultrafast laser technology and space nuclear power in the next decade to so should, however, allow for the development of a LAPPS propulsion system that would allow human exploration of the solar system to be undertaken in acceptably short times. If, for example, the thrust of present-day LAPPS can be increased by just two orders of magnitude, the Jupiter mission will be reduced to just a few months, and the Mars mission to about three weeks.

Introduction

A propulsion system that can open up the solar system and beyond could evolve from some current research dealing with laser accelerated plasmas. Recently conducted experiments at the University of Michigan and elsewhere have dramatically shown that ultrashort pulse (ultrafast) lasers can accelerate charged particles to relativistic speeds. For example, a picosecond laser pulse with only one joule of energy can accelerate an electron to MeV energy in the short space of a few microns. This takes place through the laser-generated high gradient potential that manifests itself in an electric field of a gigavolt per cm, which in turn accelerates the electron to a megavolt energy over a distance of 10 microns. As shown in Fig. 1, current achievable laser peak power of about 10^{15} Watts has been utilized in the study of relativistic non-linear optics[1], and it is expected that laser power values will be reached that will accelerate protons to energies equal to their rest mass energy. Fig. 2 shows the progress made in this area where it can be seen that proton energies approaching 100 MeV are within striking distance. In fact, a beam of protons containing more than 10^{10} protons was recently[2] accelerated by an electric field of 10 GeV/cm corresponding to a laser power of about 100 TW. Many of these achievements have been the result of developing interest in ion acceleration by compact, high intensity subpecosecond lasers with potential applications to the initiation of nuclear reactions on a tabletop.

Because of the unique properties of these laser accelerated plasmas, it should come as no surprise that we propose their utilization in space propulsion. If protons at rest mass energies can be ejected from such a system they will emerge at 0.866 speed of light and generate a specific impulse of 26 million seconds. If also a reasonable number of them, say 10^{15}-10^{20} can be accelerated by this method at a repetition rate of 10-10^3 (also deemed feasible by current thinking) then such a system will possess the propulsive capability that will make distant planets in the solar system reachable in 100's of days and some interstellar missions achievable in 10's of years. Not to be overlooked in this regard is the relative simplicity of such a system since the particles will be accelerated in the direction of the laser beam obviating the need for guiding systems such as magnetic nozzles often cited in connection with fusion-driven propulsion devices.

Physics of Laser Acceleration

In spite of the absence of a self-consistent theory of high-energy electron and ion generation in the laser-solid target interactions we can present a heuristic, plausible explanation that allows us to obtain qualitative estimates. We consider the interaction of a high-contrast laser pulse with an intensity that exceeds 10^{18} W/cm^2 at normal incidence to a target in which high-energy electrons with velocities near the speed of light are produced. We stipulate that when such a high-intensity, high-contrast laser terminates at the target surface it produces a plasma with a size of about half the laser wavelength[3] due to the longitudinal electron oscillations resulting from the oscillating Lorentz force. Near the target-vacuum surface the electrons are pushed in and out by the oscillating component of the ponderomotive force. Inside the target this force sharply vanishes. Twice in a laser period electrons re-enter the target. Returning electrons are accelerated by the "vacuum" electric field and then deposit their energy inside the target. The

electrons of this plasma are strongly heated by the laser light, penetrate deeper inside the solid target with relativistic velocities, and constitute a low density, high-energy component of the entire electron population. These high-energy electrons create an electrostatic field, which accelerates ions in the forward direction, and in turn they themselves are decelerated by the same field. An electrostatic field near the target surface has a bipolar structure with the more pronounced component accelerating ions in a forward direction. If the laser pulse duration is longer than the ion acceleration time in the layer the ions acquire an energy equal to the electrostatic energy.

The "LAPPS" Propulsion Concept

We noted earlier that a beam of one MeV protons containing more than 10^{10} particles has been successfully accelerated by a 100 TW laser beam with a one micron wavelength impinging on an aluminum foil of about one micron thickness[2]. The laser focal spot had a radius of 5 μm, and the accelerating electric field was found to be about 10 GeV/cm. We note from Fig. 2 that proton energies nearing 70 MeV had been achieved with lasers of intensity near 10^{19} W/cm^2 [4]. It is clear that in order to produce propulsive capabilities commensurate with interplanetary and other potential manned space missions from this scheme, proton beams containing 10^{18} particles at about 100 MeV energy would be highly desirable. At a rep rate of one kilohertz (which also appears to be close at hand) this propulsion device will produce about $0.2*10^3$ Newtons of thrust and a specific impulse of about $13*10^6$ seconds. Such a system, illustrated in Fig. 3, will consist of an ultrafast laser that can be fired 10^3 times per second at an appropriate solid target such as aluminum foils that are fed into a reaction chamber at the same rate. It will be driven by a nuclear reactor whose thermal power is converted to electric power by a conversion scheme such as a Brayton Cycle as illustrated.

Interplanetary Missions With LAPPS

To get a sense of how near-term LAPPS might be, we turn to some recently generated experimental results[5] and assess their merit as a foundation for a propulsion system by examining its performance in a few missions within the solar system. These experiments were performed with a one petawatt (10^{15}) laser system of 500 fs pulse duration giving rise to 500 J of energy which we assume appeared in a beam of protons containing 10^{14} particles at an average directed energy of 33 MeV. If we further assume that this system can be operated at a kilohertz (deemed feasible by current thinking) rep rate, then a high efficiency laser (e.g., 50%) will require one MW of electric power to drive it. If we assume a negligible payload, then the drymass of the vehicle will be primarily that the of power supply which in this case can be estimated[6] at 5mT. With these properties, this propulsion system will produce a thrust of about 1.5×10^{-2} Newtons and a specific impulse of about 8×10^6 seconds. When applied to robotic fly-by missions[7] from the Earth to Pluto, Jupiter, and Mars, we find that these journeys will take 67 years, 22 years, and 8 years respectively. We also note that if the thrust of the system can be increased to a modest few Newtons, then the duration of these missions will be reduced to months and weeks instead of years.
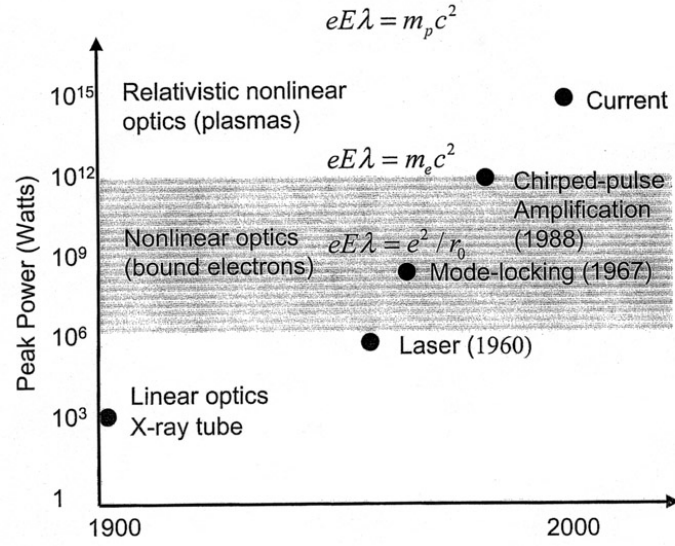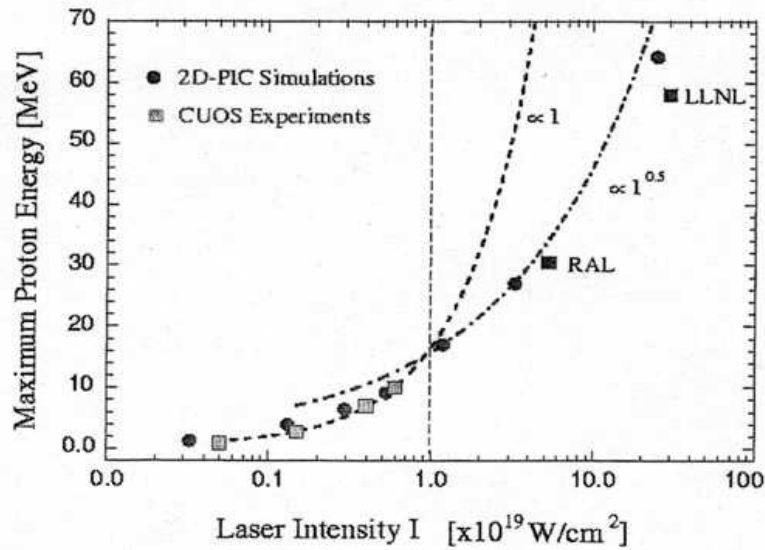
$$eE\lambda = m_p c^2$$

Fig 1. Peak Power History

Sentuko *et al.* (2000).

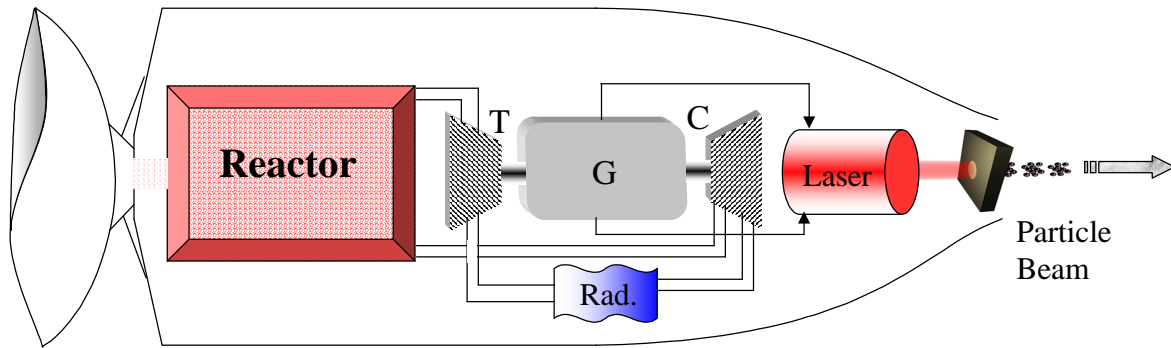Figure 2. Scaling of Maximum Proton Energy with Laser Intensity λ=1μm

Figure 3. Laser-Accelerated Plasma Propulsion System (LAPPS)

References

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